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Fuel Injector Deposits in Direct-Injection Spark-Ignition Engines

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Abstract

Controlling fuel injector deposits is recognised as a challenge for advanced direct-injection spark-ignition (DISI) engines. This paper gives a comprehensive overview of the research on formation, measurement, effect, and mitigation of injector deposits in DISI engines. Methodologies for the injector deposit studies include visual and compositional analysis. It is shown that injector deposits will reduce injector fuel flow rates, and lead to changes in spray characteristics. Consequently, spray angle and envelope are likely to be affected, and spray penetration distance as well as droplet diameter can be increased. Injector deposits are revealed to be primarily fuel-derived and created by two distinct free radical pathways, i.e., low temperature auto-oxidation and high temperature pyrolysis. Fuel compositions (olefins, aromatics, and sulphur), as well as T90 parameter, are significant factors in injector deposit formation. The worst consequences of injector fouling are pre-ignition, and engine misfiring and malfunction. Emissions, especially particulates, dramatically increase as the fuel injector becomes fouled. It appears that fuel detergent is the most effective method in controlling injector deposit formation if its chemistry and dosage rate are optimized. Outward opening piezo-driven injector configuration with a good surface finish, a sharp nozzle inlet, and a counter bore design, is useful in preventing injector deposit formation. Reducing injector nozzle temperature by methods such as designing special injector cooling passages, and improving engine design are also proven to be

helpful in reducing injector fouling. Anti-deposit coatings only delay the onset of injector deposit formation.

Keywords: GDI; Injector Deposit; Spray; Combustion; Emissions

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1 Introduction

Vehicles powered by gasoline direct injection (GDI) otherwise known as direct-injection spark-ignition (DISI) engines entered the car market in the late 1990s [1-8]. GDI engines provide benefits of high engine efficiency, low fuel consumption and emissions [1]. The global volume of GDI engines is expected to overtake that of port fuel injection (PFI) engines by 2020 [9].

GDI engines can be classified into three categories by the mixture formation process (e.g., air-guided, wall-guided, and spray-guided) [1]. In the air-guided combustion system, fuel is transported near the spark plug by a strong tumble flow generated by inlet ports with a special shape or by a flow control valve in the intake port. The air-guided combustion system is highly sensitive to bulk air motion; therefore it may suffer from severe cylinder-by-cylinder and cycle-by-cycle variations. In the wall-guided combustion system, fuel is directed to the spark plug by a specially designed piston with a cavity on the crown. Wall-guided GDI engines are commonly referred to as first generation GDI engines. In both the air-guided and wall-guided combustion system, the injector and spark plug are separated by a large distance; therefore they are called wide-spacing concepts. In the spray guided GDI system, which is referred to as second generation GDI technology, the injector is close to the spark plug (close-spacing concept). The injector of the spray guided GDI system is often centrally-mounted, differing from the side-mounted injectors near the intake port in both the air- and wall-guided combustion systems.

PFI engines commonly operate under a homogeneous-charge combustion mode and stoichiometric air fuel ratio (AFR). In addition to the homogeneous stoichiometric combustion mode, GDI engines can also run advanced combustion modes such as the stratified-charge combustion mode. In stratified-charge combustion mode, the air/fuel mixture near the spark plug is stoichiometric or slightly rich whilst in the rest of the combustion chamber it is slightly lean. The stratified-charge can be achieved by injecting all or a fraction of fuel into the cylinder during the compression stroke.

The durability of GDI engines, however, can be a challenge due to issues such as combustion chamber deposit (CCD), injector deposits, engine knocking, and pre-ignition [1, 10, 11]. Studies have shown that in order to retain the benefits of the GDI technology, the durability of GDI engines must be guaranteed throughout the vehicle life time [12, 13]. Fuel injector deposits have been identified as highly relevant, especially when various fuel properties and fuel qualities are involved [1, 14-22].

Fuel injector deposit, or injector fouling, has been observed since the introduction of PFI systems. This issue may be worsened in GDI engines, because GDI combustion systems rely more heavily on fuel spray quality, and DI injector experiences harsher operating conditions compared to those of PFI system [1, 12, 14-16, 18, 23]. More recently, new technologies developed for meeting stringent emission regulations, such as engine downsizing, stratified combustion and bio-fuels, make injector operating conditions more challenging [24]. A modern GDI injection system features a fuel injection rail or accumulator, which is maintained at high pressure typically between 80 and 200 bar depending on system configuration. It generally employs a closed loop AFR control which can adapt to significant changes in injector flow rate that may be caused by injector deposits. However the degraded spray quality caused by injector deposit cannot be solved by the AFR control; therefore measures must be taken to reduce the formation of injector deposits.

The importance of the GDI deposit issue is indicated by its impact on the desired in-cylinder air/fuel mixture distribution, which is critical to combustion and emissions in such engines [1, 18, 23, 25-33]. Figure 1 shows photographs of GDI injector deposits from the view of the (a) fuel flow exit, (b) flow entrance, and (c) injector nozzle cross section. The area near the injector tip (Figure 1 (a)) was covered by deposits which were mainly fuel derived with some lubricant oil elements such as Ca, Zn, and Mg [26]. The deposits near the flow entrance and in the nozzle (Figure 1 (b) and (c)) were fuel derived. Deposits inside the nozzle can change fuel flow rate, and deposits on the injector tip potentially distort the spray pattern [1]. Severe injector deposit issues can cause vehicle drivability problems and misfire,

and even engine malfunction and failure. Thus, GDI injector fouling is a significant concern for all GDI applications, and requires significant attention.

The objective of this paper is to review the background and the latest developments related to GDI injector fouling. The paper is organized as follows: firstly, the mechanism of the injector deposit formation, study methodologies, and the impact of fuel compositions on injector fouling are examined, followed by effects of injector deposits on engine performance. Finally, strategies for reducing injector deposits are reviewed.

2 Mechanism of Injector Deposit Formation

Injector deposit precursors are produced from the oxidation, condensation, and precipitation of unstable HCs such as olefins and aromatics due to their weak thermal stability [34]. Altin and Eser [35] described thermal stability as the tendency of deposit formation on fuel lines, valves, injectors, and combustion chamber surfaces. These fuel system deposits can be formed by two distinct free radical pathways: low temperature auto-oxidation, and high temperature pyrolysis called coking or carbon deposition. Auto-oxidation and pyrolysis are general terms describing the dominant chemical reactions in the fuel when the temperature is low and high respectively. A temperature that denotes the transition between auto-oxidation and pyrolysis is not clearly identified since the two reactions in fact overlap within a certain temperature range. Oxidation stability, which is different from thermal stability, refers to the rate at which oxygen is consumed and at which oxidative products are formed. The liquid oxidation reactions of alkyl radicals generating hydro-peroxides and other oxidized products are believed to be responsible for deposit formation [35]. At a temperature higher than 350 °C, carbon deposits are usually formed by two different routes, i.e. (1) decomposition of hydrocarbons to elemental carbon and hydrogen; and (2) polymerization/condensation of hydrocarbon species to larger polycyclic aromatic hydrocarbons which then nucleate and grow to become carbonaceous deposits.

Metal catalysis of carbon deposition often follows the decomposition route, whereas the non-catalytic carbon deposition usually proceeds via the polymerization route [35]. Moreover, characteristics of substrate surfaces (catalytic or non-catalytic) also influence the formation of carbon deposits. A non-catalytic surface may affect the heat/mass transfer in the system and act as an inert substrate to collect carbon deposits, the formation of which is thermally initiated in the fluid phase. In contrast, a catalytic surface could, in addition, interact with the reactive species and thus accelerate deposit formation [35]. It is expected that after the deposit layer is formed on the catalytic surface, the catalytic reaction is less dominant because the deposit layer stops the direct contact between the catalytic surface and liquid fuel. Therefore, the non-catalytic route is more important for deposit formation on both catalytic and non-catalytic surfaces.

Aradi et al. [25] proposed an injector plugging kinetic model beginning with two general equations:

$$\text{Net deposit rate} = \text{Deposit rate} - \text{Deposit removal rate} \quad (\text{Equation 1})$$

$$\frac{d\bar{V}}{dt} = K_1 - K_2 \times \bar{V} \quad (\text{Equation 2})$$

where \bar{V} is a dimensionless deposit volume defined by the deposit volume divided by the injector nozzle volume; K_1 is the deposit formation rate constant and K_2 is the deposit removal rate constant. An assumption was made in the Equation (2) that the deposit formation rate is zero order and does not depend on the presence of previous deposits, and the deposit removal rate is dependent on the presence of deposits and is first order. Here, the flow coefficient factor is assumed to be constant, and the flow is linear to the pressure drop across the injector nozzle. The injector flow rate is proportional to the flow area, which will be reduced by injector deposits. The deposit area equals to the deposit volume divided by an effective deposit length. Thus the fuel flow rate loss is proportional to the loss of flow area determined by the net deposit rate. The derived fuel flow loss is expressed in the Equation (3):

$$\text{Fuel flow rate loss} = -K_1/K_2 \times (1 - \exp(-K_2 \times t)) \quad (\text{Equation 3})$$

Based on the Equation (3), the fuel flow rate loss versus time is comprised of a rapid initial rate of fuel flow rate loss followed by a stabilized fuel flow loss after a sufficiently long test time; something which was observed in many publications [18, 22, 26, 36, 37]. The basic concept of injector deposits and how they affect the injector fuel flow rate are clear; however the mechanism of deposit formation is more complicated.

Kinoshita et al. [22] proposed a GDI injector deposit formation mechanism. They suggested that deposit precursors, as mentioned in [34], became nuclei depending on the environment temperature. After a fuel injection event, some residual fuel was trapped in the nozzle. Initially, deposit precursors were homogeneously dispersed in the liquid fuel (Figure 2 (a)). The proposed mechanism stated that if the nozzle temperature was lower than the T90 parameter of the fuel, most of the trapped fuel remained in a liquid state (Figure 2 (b)) and the deposit precursors were easily washed away by the following fuel injection. However, when the nozzle temperature was higher than the T90 of the fuel, most of the liquid fuel was evaporated resulting in the deposit precursors adhering strongly to the nozzle wall (Figure 2 (c)). It should be noted that deposit precursor would go through the agglomeration process; therefore in Figure 2 (a) and (c) the deposit precursors were bigger. Deposit precursors mainly refer to polar compounds [34, 38-40]. Oxidized hydrocarbon species such as hydroperoxides, which will be formed after gasoline has been stored for a long time, are also deposit precursors. Based on the research evidence available, metal elements such as Zn, Fe, Cu, Mg, Na, and insoluble salt are also suspected to support deposit formation [26, 41-44], therefore the definition of "Deposit Precursors" may have to be expanded. However, more research should be conducted to confirm this.

This mechanism proposed in [22] highlighted the importance of deposit precursors, the T90 parameter of fuel, and the injector nozzle temperature in GDI injector deposit formation. It provides some guidelines for reducing injector deposit formation. However, this mechanism is disputed in terms of the role of nozzle temperature and the T90 of fuel in GDI injector formation. Reducing nozzle temperature

below T90 does not always lead to reduced injector deposit formation; increasing nozzle temperature above T90 does not always promote injector deposit formation. The details will be introduced later in the Section 4.1.

3 Methodologies for Injector Deposit Study

Various methods are available for assessing GDI deposits and their effects on the fuel injection system. These methods range from quantitative flow rate tests to complex chemical analysis of the deposit structure and composition. At the end of this section, methods for accelerating GDI injector deposit formation are also reviewed.

Apart from the flow rate test, the analytical techniques for characterizing deposits can be classified into three groups. The first group covers visual analysis like high-speed spray imaging, optical microscopy and scanning electron microscopy (SEM) [14, 22, 25, 26, 37, 45-47]. The next group are the elemental analysis, typically including energy dispersive X-ray fluorescence spectroscopy (EDX or EDS) [48]. Finally, there are compositional analyses like Fourier Transform Infrared Spectroscopy (FTIR) and Gas Chromatography (GC) coupled with a mass-spectrometer (MS), namely GCMS, which is able to identify and quantify volatile compounds.

3.1 GDI Injector Flow Rate Loss

The primary indication of injector fouling is a reduction of flow rate. Bench tests consist of either static flow measurement (constant flow through an open injector), or dynamic measurement (pulsed flow). In order to evaluate injector flow losses in-vehicle, a common practice is to use the injection pulse width provided by the engine control unit. The injector pulse width will be adjusted to achieve stoichiometric combustion by using closed-loop AFR control, if the fuel injector flow rate is changed by the presence of injector deposits.

3.2 GDI Injector Spray Visualization

Lindgren et al. [29] used spray visualization technologies to study the spray of GDI injectors. The test was conducted in a chamber with a back pressure of 150 kPa and a temperature of 20 °C, which simulated in-cylinder conditions at the time of injection corresponding to an engine speed of 2000 rpm and 200 kPa BMEP. The injection pressure was set to 50 MPa. Figure 3 shows the spray from clean and fouled injectors using a Phase Doppler Particle Analyser (PDPA). It is found that the pre-jet of the fouled injector was more dense and penetrated faster compared to that from a new injector. Controlled by the injection control system, the pilot jet of fuel was injected before the main jet of fuel was injected. The quantity of the main fuel jet was larger than the pilot jet of fuel. Droplets in the pilot jet from the fouled injector had a 30% higher mean velocity and up to a 17.5% larger mean diameter.

In general, the spray of fouled injectors tends to atomize less and thus has a longer spray penetration distance. The original symmetrical spray can even become asymmetrical if the injector is plugged to some extent.

3.3 Deposit Visualization

Typical magnifications of optical microscopes are around 1000 times, which offers a good resolution. Digital microscopes are capable of providing 3D display. Optical images help to assess the form and the principal structure of injector deposits. They provide researchers a first visual indication of the nature of deposits. Generally, magnification is limited by the wavelength of the light source.

SEMs use an electron beam as the light source. The wave length of electrons are shorter than that of the visible light; therefore resolutions of 0.2 to 0.5 nm can be achieved [49]. Many researchers have taken SEM images of injector deposits [14, 22, 25, 26, 37, 45-47].

3.4 Elemental Analysis

X-ray fluorescence spectroscopes use the chemical/physical phenomena wherein atoms of one element emit characteristic X-ray spectra, when they are exposed to high energy particles like electrons. These spectra are unique for each element.

In the field of injector deposit analysis, EDX/ EDS systems are coupled with SEMs [41, 43, 48, 50]. The combination of SEM and EDX/EDS makes it possible to generate an elemental profile of deposits on injector surfaces. In these studies, researchers found further elements in addition to carbon, oxygen, sulphur, and nitrogen, which have their origin in fuels and air as expected. For example, Carlisle et al. [43] found further elements, like phosphorus, Ca, and Zn, which originated from the engine lubricant. Fernandes et al. [41] used the same technique for injector analysis. In addition to the above mentioned elements, he also detected Na. The analytical techniques above are however not able to give concrete information about the compounds or functional groups within the deposits.

3.5 Compositional Analysis

FTIR utilizes the principle that certain molecules absorb certain infra-red radiation. The typical wavelengths used are between 400 and 4000 nm. The adsorption of IR radiation follows the Lambert-Beer law; therefore, the adsorption is correlated to the concentration of specific bonds. Bacho et al. used FTIR to compare deposits formed in engine tests and manufactured carbon black [46, 51].

With GC, volatile components in deposits can be analysed. Common gasoline GC methods are typically quantitative (e.g. EN 1601 “Determination of organic oxygenate compounds”). When coupling mass spectra (MS) to a GC, it is possible to detect individual single components. Barker et al. [42] used GCMS to identify organic deposits (after hydro-pyrolysis) taken from diesel high pressure fuel injection equipment.

Thermo-gravimetric Analysis (TGA) is a technique in which the mass of a substance is monitored as a function of temperature or time as the sample specimen is subjected to a controlled temperature program in a controlled atmosphere [52]. It is used for the characterisation of engine deposits [53, 54]. The methods associated with TGA can be segregated into three groups depending on the application. The first is a single temperature ramp programme to measure differences in the oxidation process between deposits formed while using different types of fuels and additives [55]. The second type of test is a more elaborated two-stage method enabling determination of volatile organic and non-volatile organic fractions of deposits. Deposit samples are heated in an inert atmosphere such as N₂ at a chosen temperature rise rate i.e. 10 °C/min from ambient to 500 °C (or other temperatures). Air can be introduced at that temperature, following which the sample is held at 500 °C for some time to oxidise its components (i.e. 30 minutes). The sample's total weight loss and rate of weight loss are recorded [56]. The third type of test is when TGA is used for verification of thermal stability of individual additives as suggested by Ullmann et al [57].

The above analyses can also be classified into destructive or non-destructive methods. If a researcher wants to know what deposits are within an injector, non-destructive analyses like EDX/EDS become destructive from the point of view of the injector. Disassembling injectors often means the use of destructive techniques such as cutting or cracking, which makes it impossible to use the injector for further operational tests like spray and flow measurements.

With currently available analytical techniques, it is possible to describe injector deposits broadly; however, these techniques still cannot be used to explain the deposit formation mechanism. It is down to the judgement of the researcher to combine the analytical results with the known history of deposits and other tests to create a complete picture.

3.6 Methods for Accelerating GDI Injector Deposit Formation

In order to assess the effect of different fuels, detergents, and hardware designs on injector fouling, it is often necessary to operate controlled laboratory experiments. A number of test cycles, which are based upon PFI technology [14, 58-60], have been developed for both vehicle and engine dynamometer tests. These test cycles are designed to replicate normal vehicle operating conditions. There is also a question of whether accelerated tests are able to represent real-field conditions. Bacho et al. [51] found that FTIR spectral analysis of GDI injector deposits from accelerated laboratory tests were similar to that from real-field vehicles using commercial gasoline. Therefore they confirmed that deposits produced in the accelerated laboratory test represent real world deposits.

The majority of accelerated methods use special fuels to investigate the effects of certain chemical and physical properties on injector deposit formation, or to represent the worst case conditions for GDI deposit formation. Many studies focus on the engine operating conditions known to increase deposit formation. The key parameters controlled are the injector tip temperature, fuel injection pressure, coolant temperature, and soak period; all of which are also used in the PFI injector fouling test [36, 51, 61]. Several researchers have developed injector tip temperature maps and use those maps to determine the number of engine cycles required for accelerated tests [47, 51]. Vehicle tests are often related back to field or standard driving cycles [23, 26, 37]. Summaries of engine and vehicle tests reported in the literature are given in Table 1.

The test cycles shown in Figure 4 differ in the engine speed, injection pressure, test duration, and test mileage depending on tested fuels, oil and engine designs. It should be noted that most researchers have used low engine speeds (1500-2500 rpm) and medium engine loads in the study of injector deposit formation. The following is a summary of the findings revealed by the tests using those driving cycles:

1. Measurable GDI injector deposits can be formed during continuous engine operations.
2. Injector nozzle temperature affects injector deposit formation.
3. Fuel composition is a significant factor concerning injector deposits.
4. The fuels with low T90s, high olefins, and high sulphur are shown to promote injector deposit formation.
5. Low injection pressure is shown to accelerate injector deposit formation.

Most methods mentioned above use stationary test conditions. This is because the purpose of those tests is to achieve fast injector fouling with typical engine loads and speeds. Compared to transient states, it is easier to maintain a constant injector tip temperature using stationary state conditions. For benchmarking, the total running time in most cases takes several tens of hours. The publication of [36] used the shortest test time (16 hours), and achieved a flow rate loss of more than 20%. The standard ASTM D5598 Cycle method which contained a few transient stages and some soaking stages, took 8000 km running to reveal a significant flow rate loss even for fuels without detergents [23]. The content above also seems to indicate that pro-fouling strongly depends on the fuel and injector type, which means a careful design of a testing cycle is needed. On the other hand, those stationary tests cannot well represent the real transient conditions, because these road running states vary the temperature of the injector tip frequently. Currently there is little information available for the cycle design which mainly focuses on the impact of low loads and transient stages; therefore further study is necessary.

4 Impact of Fuel on Injector Fouling

The composition of gasoline on the market varies with country, region and season. The market fuel standards in different regions of the world also vary significantly, as can be seen in Table 2 comparing the EU, US, and China 2013 specifications.

4.1 T90

There are two hypotheses about the role of the T90 parameter in GDI injector fouling. The first one is that fuels with higher T90 tend to have less severe injector fouling. The second one is that, for a certain fuel, a nozzle temperature lower than T90 will lead to less severe injector fouling than a temperature higher than the T90 value.

There is research evidence supporting the first hypothesis. Kinoshita et al. [22], as mentioned in Section 2, found that fuel with a higher T90 led to lower flow rate losses than fuel with a lower T90. Another study drew a similar conclusion from experiments on a 2.2 L four-cylinder GDI engine operating at an engine speed of 2500 rpm. 11 fuels were tested and their properties are listed in Table 3 [26]. Five engine loads were studied with five injector nozzle temperatures of 120, 140, 157, 173 and 184 °C. The injector fuel flow rate losses for 11 fuels experiencing five injector nozzle temperatures are listed in Table 4. When comparing the results of various fuels at the same nozzle temperature, the fuels with the same olefin and sulphur content but lower T90 consistently led to higher fuel flow rate losses.

The second hypothesis is controversial. Kinoshita et al. [22] pointed out that when the injector nozzle temperature is higher than the T90 parameter of the fuel, the injector fouling is more severe than the corresponding case, where the temperature is lower (see Figure 5). This finding is not supported by [26]. None of the 11 fuels followed the pattern in Figure 5. The data in Figure 6 is from [26], and shows the results for Fuel 4, Fuel 7, Fuel 10, and Howell EEE. It is clear that a nozzle temperature

higher than T90 does not always lead to low injector deposit formation. For example, injector flow rate losses at a tip temperature of 184 °C were lower than the cases of a tip temperature of 173 °C. The potential explanation is that the formation rate and removal rate both increase with temperature. However when the temperature exceeds 173 °C, the removal rate overtakes the formation rate. It is also clear that when the nozzle temperature was much lower than T90, such as the case when it was below 140 °C, the injector flow rate loss for all 11 fuels were low.

Carlisle et al. concluded that T90 was not a statistically significant parameter regarding the deposit formation in an air-assisted direct injector [43]. This conclusion was potentially related to the unique characteristics in air-assisted injectors comprising of a conventional fuel injector and an interface region providing a path between the air and fuel circuits and injectors.

4.2 Sulphur

The effect of sulphur on injector deposit formation was studied in [26, 36, 41, 47, 62]. It seems that there is not a consensus about the effect for fuels with sulphur content ranging from 5 to 310 ppm. As listed in Table 3 and Table 4 [26], Fuel 1 was similar to Fuel 5 except for a lower sulphur content (30 ppm versus 150 ppm). With the injector nozzle temperature of over 140 °C, Fuel 1, which had a lower sulphur content, led to higher injector deposit formation than Fuel 5. The same trend can be found in Fuel 2 and Fuel 6, and Fuel 3 and Fuel 7. However this trend was not observed in Fuel 4 and Fuel 8, between which there were limited differences in injector flow rate loss. Ashida et al. [47] reported that alkylate with 10 ppm and 310 ppm sulphur contents had limited differences in injector fuel flow loss (4% and 3.8%).

The data from Rivere et al. [36] shows that a fuel with 155 ppm sulphur content had similar injector deposit problems to the fuel with 90 ppm sulphur content. However, the fuel with 90 ppm sulphur content had only 10% olefin content whilst the fuel with 155 ppm sulphur content had 15% olefin

content. It is not clear how those two fuels were prepared. Therefore, the comparison of flow rate loss between those two fuels is not fair and could be inferred by the olefin factor. Research regarding fuel with high sulphur reached a consensus [41, 62]. Fernandes [41] carried out a test on a chassis dynamometer and found that a vehicle running with a high sulphur content fuel (523 ppm) required less mileage to reach a 30% injector flow rate loss compared with a low sulphur content fuel (20 ppm). Saito [62] found that fuels with sulphur content higher than 500 ppm had a greater tendency of injector deposit formation.

Hydrotreating is an established refinery process that will not only reduce sulphur content within fuel, but reduce the number of double bonds within the fuel; therefore, the fuel becomes more stable. It is expected therefore that hydrotreating will help reduce GDI injector deposit formation.

4.3 Olefins

The effect of olefin concentration on deposits was investigated in [26]. As listed in Table 3 and Table 4, four groups of fuels (Fuel 1 & Fuel 3, Fuel 2 & Fuel 4, Fuel 5 & Fuel 7, and Fuel 6 & Fuel 8) had similar fuel properties except for olefin contents. An increase of deposit formation was observed in fuels with higher olefin contents. Uehara et al. [63] suggested that larger molecular weight olefins led to a higher injector deposit tendency.

From a chemical perspective, olefins are highly reactive components due to their unsaturated carbon bonds and weak thermal stability; therefore, olefins are suspected to assist deposit formation through low temperature auto-oxidation, and high temperature pyrolysis [64]. More detailed discussion about the thermal stability is given in Section 2.

4.4 Aromatics

Very limited studies have been conducted on the effect of aromatics on injector deposit formation. A study into blending various aromatics with alkylate was reported in [47]. The details of fuel properties and fuel flow rate losses are also shown in Table 5. The results indicated that Fuel 3 (30 vol% n-propylbenzene) suppressed the injector deposit formation whilst other aromatics promoted the injector deposit formation. The difference seemed to relate to the number of alkyl substitutes and their positions on the benzene ring. It is noticeable that the base fuel had different T90 than all the other fuels; the differences in injector flow rate loss are caused by both the effect of T90 and blended aromatics.

4.5 Alcohol

It is widely acknowledged that ethanol is a clean fuel in terms of soot emissions [65-67]. Since soot and injector deposits are primarily composed of carbon, it is of interest to discuss the effect of ethanol on GDI injector deposit formation.

Unlike gasoline, ethanol is a single component fuel with no double bond, making it more thermally stable compared to olefin components in gasoline. The ethanol molecule has only two carbon atoms, and most importantly, it has one oxygen atom, giving it an oxygen content of 35%. Self-supplying oxygen during combustion is the main reason for its low soot emissions. Even though the mechanism of PM and deposit formation in the GDI injectors are potentially different due to the temperature of PM formation being significantly higher than that of GDI injector deposit formation, it is expected that ethanol leads to less deposit formation in injectors. Besides, ethanol has a higher latent heat value; therefore it leads to lower injector nozzle temperatures compared to gasoline, which is supported by Taniguchi et al. [68]. They measured the injector temperature in a 6 cylinder GDI engine at an engine speed of 3200 rpm, 0.9 bar mean effective pressure, stoichiometric AFR, and optimized spark timing. They found that the injector nozzle temperature for pure ethanol is nearly 25 °C lower than that for gasoline.

In addition to the advantage of using ethanol to control GDI injector deposit formation, there is one disadvantage, which is that ethanol has a lower boiling point compared to gasoline. Ethanol blended gasoline has a lower T90 compared with gasoline alone.

There are many publications studying the effect of ethanol on GDI injector deposit formation. Taniguchi et al. [68] tested various ethanol blend fuels. The engine was modified to have a reduced injection pressure of 40 bar, down from the original 120 bar. The injector tip protrusion was also increased to raise injector tip temperature. Figure 7 presents the comparison of spray shapes, nozzles, and nozzle holes after a 10 hour durability test. The test condition is also shown at the bottom of Figure 7. It is obvious that ethanol, either in a pure or blended form, was able to suppress deposit formation during dirty up tests. Ashida et al. [47] compared the injector flow rate loss between base fuel alkylate and blended fuel with 10 vol% ethanol. They observed that blended fuel led to less flow rate loss (4% versus 1.5%) after an 8 hour test. Dumont et al. [69] tested E85 in a vehicle for 5000 miles and there were no visible deposits in the fuel metering orifice and no injector performance issues were observed.

The research of Taniguchi et al. [68], Ashida et al. [47], and Dumont et al. [69] provides evidence that ethanol is able to keep the injector clean. Apart from keeping the injector clean, ethanol is also able to clean up fouled injectors. Dumont et al. [37] found that E10 (10 vol% ethanol in gasoline) was able to clean the injectors, as a result of which, the injector flow rate loss was reduced from 18.9% to 5.5% after a 48 hours of clean up test, which is a result of reduced deposit formation and increased deposit removal. In a later study by Russell et al. [61], the effect of various market specific ethanol blended fuels (both corn and cellulosic based) on injector flow rate of were examined on a four-cylinder 2.0 litre GDI engine. It was found that the fuel flow rate reduction resulting from injector deposit build-up during a purposely designed deposit build-up test was statistically equivalent between the different samples of ethanol used in the study. The test fuels used were within the specification limits of ASTM

D4806 'Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel'.

Studies about other alcohols, especially methanol that is widely used in China in blended forms, are of interest. While it has not been proven, it is suspected that methanol may cause severe injector plugging problems, due to its corrosive properties. On the other hand, methanol has a high latent heat value, even higher than that of ethanol, giving it is an advantage in lowering injector nozzle temperature. Overall its impact on injector deposit formation remains unknown, and requires investigated further.

4.6 Metallic and Insoluble Salt

Metal elements such as Zn, Fe, Ca, Mg, Na, and K, and insoluble salt are detected in fuel injector deposits [26, 41-44, 69]. The metal elements are introduced either by contamination, lubricants, or additives, such as methylcyclopentadienyl manganese tricarbonyl (MMT). Many publications report that the use of MMT in the fuel as an octane booster led to increased HC emissions, CCD, and spark plug [70] and catalytic deposit formation [71-74]. Roos et al. [75] conducted a survey about injector repairs and replacements in three cities in America and Canada where gasoline fuel was sold with and without the additive MMT. They found that there was no statistically significant differences in the number of repair or replacement of fuel injectors in cities where gasoline contained MMT, compared to cities where gasoline didn't contain MMT. Deposits near the injector tip appear to be primarily fuel-derived but contain lubricant elements Ca, Zn, and Mg. Internal injector deposits inside the nozzle are only fuel derived. Dumont et al. [69] detected Na, K, and sulphur in the deposit using EDX and further identified sulphur salt using FTIR. Information concerning the quantitative impact of the metal element concentration on GDI injector deposit formation is not available; therefore it remains a future research interest.

5 Effects of GDI Deposit on Engine Performance

The effects of injector deposit on engine performance and emissions have been widely reported [1, 13, 14, 28, 29, 37, 43, 76-79]. An accelerated deposit formation test was carried out on a four-cylinder GDI engine, using a fuel with additives known to accelerate deposit formation [79]. After a 55 hour steady state dirty-up test (5 bar BMEP and 2000 rpm engine speed), a 23.5% injector fuel flow rate loss was observed, along with an increase of 20%, 93%, and 2.45% of HC, CO, and fuel consumption respectively. The maximum power output of the engine was reduced by 1% and the corresponding fuel consumption was increased by 2.2%. As a result of injector fouling, pre-ignition was observed. An additional 36 hours clean-up test was able to reduce CO and HC emissions to the same level as recorded at the beginning of dirty-up test. CO and HC emissions in the 55 hours' dirty-up test and 36 hours' clean-up tests are presented in Figure 8. Sandquist et al. [28] studied injector fouling in a wall-guided (wide-spacing concept) stratified charge GDI engine. They concluded that injector fouling was responsible for 80% increased HC emissions after 60 hours of a dirty-up test, which fell back to the initial level when the fouled injectors were replaced with new injectors. Misfires and/or partial burn were observed, and even became unacceptable for some worse case fuels.

There are two root reasons for the deteriorated engine performance and increased HC emissions: first, a distorted spray pattern due to injector fouling; second, deposit formed on the injector tip. Any deviations from optimized spray patterns, such as changed spray angle, asymmetric spray envelope, longer penetration distance, and increased droplet size distribution, have negative impacts on the engine performance and emissions [18, 23, 25-27]. Wall-guided, air-guided, and spray-guided engines running in the stratified combustion mode are more sensitive to fuel spray pattern changes than engines running in the homogeneous combustion mode [1, 16, 18, 23, 80]. The mixture preparation relies on several factors such as spray pattern, in-cylinder charge flow, spray and wall interaction, fuel property, and in-cylinder temperature and pressure [30-33, 81]. The direct consequence is increased fuel impingement and non-optimum combustion, or even misfire; thus engine power output is reduced and

emissions are increased. There is research evidence showing that an increased mass of fuel impinged on the cylinder liner due to higher spray jet velocity and larger droplet diameter resulting from fouled injectors [29]. More information about spray changes caused by injector fouling is available in Section 3.2.

Deposits on the injector tip, even though they do not lead to flow rate loss, can have a negative impact on engine performance. Deposits will pick up liquid fuel droplets, which cause diffusive combustion thus it leads to poor emissions. This is proven by Berndorfer et al. [82] by using high speed imaging in an optical engine. They observed diffusion combustion near the injector nozzle.

The impact of fouled injectors on PM emissions has been studied by the authors' research group in a single cylinder spray-guided DISI research engine [83]. Two fouled and one clean DI injectors were tested with gasoline and ethanol engine fuel. PM emissions were measured by a Scanning Mobility Particle Sizer Spectrometer (SMPS3936). Figure 9 shows the effect of fouled injectors on particle number (PN) and PM emissions when using gasoline as a fuel (engine speed=1500 rpm, $\lambda=1$, IMEP=6.5, 7.5, and 8.5 bar). Injector 1 and Injector 2 had 8.5% and 5.3% flow rate loss respectively. Injector 3 was a clean injector used as the benchmark. Injector 3 consistently led to the lowest total PN and PM emissions (see Figure 9 (a) and (d)). The maximum difference was observed at the highest engine load 8.5 bar IMEP, in which the PN and PM emissions of fouled Injector 1 were 58% and 300% higher than those with clean Injector 3, respectively.

Particle size distributions are composed of particles with different natures: (a) nuclei HCs which mainly compose the nucleation mode, and (b) soot agglomerates with HCs condensed or adsorbed on their surface, which compose the accumulation mode [84]. By breaking down the total PN and PM emission into the nucleation mode and accumulation modes, it is clear that the total PM emission of injector 1 in [83] was increased mainly because of the increase of the accumulation mode PM

emissions. In other words, soot emissions were much higher for the fouled injector than the clean injector. This result is in agreement with Berndorfer et al. [82] in which higher soot emission was found with a fouled injector resulting from diffusive combustion near the injector tip due to liquid fuel absorbed on deposits. The research by authors' research group [83] also revealed that when ethanol was used as fuel, the PM and PN emissions were not as affected by injector conditions as gasoline was, for the reasons given in Section 4.5, i.e., ethanol has much better atomisation and vaporisation characteristics and in addition, it is oxygenated.

6 Strategies for Injector Deposit Reduction

There are extensive studies on GDI injector deposit reduction methods, mainly focusing on fuel detergents, injectors, and engine design.

6.1 Detergents

In China, the majority of fuels are supplied without detergents at the distribution level, and the use of detergents can be limited to aftermarket treatment products added to the fuel tank. In the US, a minimum detergent content is demanded by the EPA [85]. The use of detergent within the EU is neither demanded nor limited.

There are many deposit control detergents designed for combustion chamber deposits and intake valve deposits, such as polyether amines, polyolefin amines, and alkenyl succinimides. Detergents work by protecting the metal surface, dispersing the deposit precursors, and cleaning the metal surface. Fuel detergents generally have long chain hydrocarbons with polar head groups at one end of its molecule. The other group in the fuel detergent molecule does not have a polar property. The polar head group has a property of easily attaching itself onto the metal surface, forming a protective surface, and thus preventing the deposit precursor from depositing onto the metal surface; this process is referred to as 'protection'. The polar head group can also attach to deposit precursors therefore keeping the deposit

precursors dispersed in the liquid; this process is referred to as 'dispersion'. In the case of pre-existent deposits on the metal surface, the detergent with a polar head group will pick up deposits and help to remove them from the metal surface. Consequently the detergents molecules break away, taking some of the deposit with them, which is referred as 'detergency'.

There is a report claiming that conventional deposit control detergents designed for controlling CCD and intake valve deposit were also effective in keeping clean and cleaning up GDI injector deposits [86]. Many studies have been carried out on PFI injector deposit control detergents [87-91], however investigations of detergents for GDI injector deposits were only started in recent years [18, 25, 36, 37, 47]. A study of two types of detergents (Manniches and polyether amines (PEAs)) were conducted in a GDI research engine [25]. Results show that Mannich detergents were more effective in injector deposit control than PEAs. In another study of GDI injector deposit detergents (Manniches, PEAs and polyisobutylene amines) [36], it was found that some chemicals were more effective than the other at the same treatment rates. Polyisobutylene amines performed the best amongst the three tested detergents. In the study of [37], four detergents were tested, and it was found that three of them effectively removed injector deposits. Nevertheless, in almost all the literature, the performances of different types of detergents were difficult to assess because of the lack of detailed information, or contradictory results of similar detergents.

The concentration of detergents needs to be optimized, since evidence shows that detergents may accelerate combustion chamber deposit (CCD) formation [63, 92]. Other publications show that further increasing the concentration of detergents from the optimised concentration did not have any benefit in controlling injector deposit formation [36, 47]. According to the literature, the optimised treatment was between 400-1000 ppm, depending on the type of detergents being used.

There is some evidence showing that certain detergents can help control GDI injector deposit formation when engines were running in the stratified combustion mode, but not in the homogenous mode [43]. A Mannich detergent formation (Man C-2(B)) had a good clean-up effect in the stratified operation, but an opposite effect was observed in the homogenous operation [18].

Most literature available about detergents concerns PFI injectors. Even though the research of PFI detergent is highly valuable for the design of DI detergent, there are differences between DI and PFI detergent packages due to the differences in the deposit formation mechanism. Economically, it is undesirable for fuel stations to provide separate gasoline detergents to PFI and DI vehicles.

6.2 GDI Injector Design

Studies have been conducted to reduce injector temperature for the purpose of reducing injector deposit formation. The methods include changing cooling passages in the cylinder head [22], adding an injector socket with a high thermal conductivity [22], adding insulating material on the injector surface to reduce heat transfer from hot combustion gases to injectors [22, 93, 94], and using coatings with a higher thermal conductivity to conduct heat away from injectors [95]. Katashiba et al. [96] examined a method of reducing the heat transfer with a combination of reduced injector surface area exposed to the heat source and the incorporation of a front seal (Figure 10). Injector tip temperature was reduced from 185 to 160 °C by using a narrow opening adaptor and further reduced to 121 °C by replacing the injector rear seal with a front seal.

All of these methods provide simple and effective solutions for reducing injector tip temperature. However, low injector tip temperature may have a negative effect on the spray pattern and combustion stability [97]. High injector temperatures lead to a compact spray and smaller fuel droplets [30, 97, 98]. Increasing the injector temperature decreased the spray penetration distance and increased the spray width in slit injectors [97]; however, a reverse trend was observed with a swirl injector. A slit injector

is a type of injector that produces a fan spray structure. Swirl injectors generate thin liquid sheets by opening the needle inwards (inward opening). Therefore, it can be expected that for slit injectors, by reducing the injector tip temperature, the benefit of reduced injector deposit formation will be offset by the degraded spray quality, whilst for swirl injectors, decreased injector deposit formation and higher spray quality can be achieved simultaneously by reducing injector tip temperature. When using the strategy of lowering the injector temperature, consideration should be paid to match injector types.

Anti-deposit coatings on the key injector surface, such as fluorine-coating amorphous hydrogenated carbon films [99] and inert amorphous silicon [100], were also tested for controlling deposit formation. However, researchers found that anti-deposit coatings failed to achieve a breakthrough in preventing deposit layer formation on GDI injectors [82, 100]. The explanation is that those anti-deposit coatings are only able to delay the onset of deposition. Once a deposit layer is formed, the coated and uncoated injectors exhibited limited differences in the deposit formation. Therefore, anti-deposit coatings are not effective in controlling injector deposit formation.

Better nozzle surface finishing and optimized nozzle shape are also beneficial for suppressing injector deposits [100]. Laser drilling holes with a smooth inner-surface and sharp inlets could reduce injector fouling and the interactions between fuel jets [101]. Sharp hole entrances also contributed to suppress injector deposit formation, probably due to increased cavitation and turbulence [100, 101]. According to [100], a protruded injector tip reduces the likelihood of the spray impacting the protruded seat by providing a roughly uniform step hole depth around the circumference of the step. The protrusion also reduces the likelihood of the spray contracting the face of the seat or combustion chamber surface by positioning the hole exit further away from these surfaces. The temperature profile of the seat is also affected by the protrusion.

Since deposits in the injector nozzle are mainly fuel-derived, any attempt to reduce the residual fuel inside the nozzles contributes to a reduced deposit formation tendency. Reducing the SAC volume, or even using valve covered orifices (VCO) provides benefits in the control of residual fuel [100, 102-104]. In the VCO layout, the injector orifices are completely covered by the injector needle when the valve is closed. No fuel escapes from injectors after the injector event ends; therefore VCO layout can also reduce the diffusive combustion caused by fuel leakage. Besides, the step hole or counter bore in the outlet side can decrease the impact of the deposit formation [100].

The robustness of injectors varies with injector geometry and type. Since deposit formation is inevitable with the use of hydrocarbon fuels, injectors with better tolerance to the presence of deposits is desirable [1]. Currently, there are several injector types, including swirl, multi-hole, and outward opening injectors. The spray of a swirl injector is more flexible than that of a multi-hole injector [105]. For a given deposit layer inside the swirl chamber, circumferential and axial flow resistances inside the nozzle, which have opposite effects on the flow rate, are both increased [105]. Zhao et al. [1] pointed out that a small amount of deposits on a swirl injector could change the spray-symmetry. Multi-hole injectors, which also open inwards, provide better flexibility in the spray pattern by changing the position and orientation of the holes, making asymmetrical spray patterns possible. However, multi-hole injectors are highly vulnerable to deposits formed inside the nozzle because injector flow is highly sensitive to the change in the dimensions of the internal geometry [14, 25]. Unlike swirl and multi-hole injectors, outward opening injectors open the needle outwards and generate a hollow cone spray resembling that of swirl injectors. Outward opening injectors have less cycle-to-cycle spray angle variation compared to swirl injectors, and do not have the poorly atomized pre-spray structure which exists in most swirl injectors [106, 107]. Outward opening injectors have the potential to address typical problems related to spray-guided GDI configurations (close-spacing concept) due to better air utilization than multi-hole sprays, good penetration during early injection, and the spray angle being almost independent of backpressure [108]. The conical shape and zero SAC volume of the nozzle

passage of outward opening injectors prevents carbon formation, and the robustness of the inward opening injectors against fouling can be improved by appropriately designing the needle tip and seat [109]. The deposit built up may only influence spray pattern, not the flow rate [108]. The new generation of outward opening piezo-driven injectors have better performances than, or comparable to those of solenoid injectors [109-111]. Preussner et al. [105] compared these three types of injectors. They concluded that the multi-hole injectors are the least robust against fouling, whilst outward opening injectors are the most robust. Thus outward opening piezo-driven injector design is a promising technology for future GDI injector deposit reduction.

Cavitation in the gasoline fuel injection system is a topic of interest in recent years [112-114]. The injector temperature can have a significant impact on the cavitation formation [113]. A strategy of increased cavitation utilized for injector deposit control in GDI engines is uncertain; therefore it requires more investigation.

A summary of optimized injector configurations in inhibiting deposit formation are listed in Table 6.

6.3 Engine Design

In commercial GDI engine development, engine design has to cover a wide range of requirements. Injector deposit formation can exhibit a high sensitivity to combustion systems. Compared with the air-guided GDI system, the spray-guided GDI system has a more significant injector tip wetting problem due to lower availability of air motion near the injector tip [1]. Depending on the injector location, the thermal environment of the GDI injector varies, with higher temperatures observed as the injector is located closer to the spark plug and exhaust valve. In the wall-guided GDI system, the fuel injector experiences a low tip temperature due to a long distance to the flame front and a strong air movement around the injector tip, reducing the amount of residual fuel. Thus it is possible that for the spray-

guided GDI engines, injectors could experience more deposit problems compared to the wall-guided GDI engines [26].

Figure 11 shows the effect of injector locations (central versus side mount) on the injector nozzle temperature [96]. The longer the distance between the spark plug and the injector, the lower the injector nozzle temperature; therefore lower injector deposit formation will be expected. Different engine types have various spark plug and injector configurations. Bacho et al. [51] studied the GDI injector mounting location and observed that centrally mounted injectors tended to experience larger flow rate loss (7.2% versus 2%) compared to side mounted injectors. Another study also support the point that in the spray-guided GDI engines, injectors could experience more deposit problems compared to the wall-guided GDI engines [26]. A primary issue for the centrally located injector was to reduce the spray structure changes resulting from the deposit build up near injector nozzle holes [96].

Literature shows that injector flow rate loss varied with the location of the injector in the cylinder [36]. Due to the difference in cylinder-to-cylinder injector flow rate losses [36, 41], cylinder-to-cylinder combustion variation was therefore introduced, which in turn increased the variation of the injector-to-injector deposit formation.

Increasing fuel injection pressure is proven to be an effective way of reducing deposit formation [51]. A higher injection pressure suppresses the injector deposition formation by increasing the deposit removal rate, and also reduces PM emissions in GDI engines [115, 116]. Currently, the injection pressure of DISI engines is in the range of 80-200 bar, whilst the injection pressure of diesel engines is around 2000 bar. Increasing injection pressure in gasoline engines will help reduce injector deposits as well as improving combustion quality, but will increase the parasitic losses caused by the fuel injection system.

7 Conclusions and Future Work

A comprehensive literature review of GDI injector deposits has been provided. The following is a summary of key findings.

1. GDI injector deposits have been found to be primarily fuel-derived in the literature sources. The presence of injector deposits can reduce the injector fuel flow rate and in some cases cause destructive changes to the desired spray patterns, such as changed spray angle, prolonged spray penetration distance, asymmetric spray envelope and larger spray droplet diameter. Optimised spray is essential to the fuel/air mixture preparation, thus injector fouling can cause deteriorated combustion and emissions. Severe injector deposit problems can affect vehicle drivability and increase misfire. An increase in emissions is also indicated to result from injector fouling.
2. The primary parameters found in the literature sources are associated with injector deposit formation are the T90 parameter of the fuel, the injector nozzle temperature and fuel injection pressure. Fuels with a high T90, reducing injector nozzle temperature low enough, such as 140 °C, or increasing injector nozzle temperature high enough, such as 184 °C, lead to less injector fouling issue. Higher injection pressure contributes to increase the deposit removal rate, therefore suppress injector fouling.
3. Fuel composition is a significant factor in injector deposit formation. Injector deposits can be created by two distinct free radical pathways: low temperature auto-oxidation, and high temperature pyrolysis namely coking or carbon deposition. High olefin contents increase the tendency of injector deposit formation due to their high reactive unsaturated carbon bond. High sulphur content (400-500 ppm) can lead to increased injector deposit problems.

4. Detergents can reduce injector deposit formation depending on chemistry and dosage rate. Improving injector designs (outward opening piezo-driven injector) with good surface finish and counter bore design can be beneficial in preventing injector deposit formation. Anti-deposit coatings only delay the onset of injector deposit formation; however, they are proven not work well after deposit layer is formed. Strategies of insulating or cooling the injector tip were shown to be effective in reducing the deposit formation in certain conditions.

Based on the review above, the authors believe that there are several key areas requiring further investigation for controlling fuel injector deposits:

1. The mechanism of GDI injector deposit formation is not completely understood. The only proposed mechanism available in the literature concerns the deposit precursors, the T90 parameter of the fuel, and injector nozzle temperature. There is a lack of agreement of the role of nozzle temperature and T90 in GDI injector formation. Therefore, a much more detailed mechanism is required.
2. CFD modelling will save significant time and cost in improving the understanding of the effect of injector deposits on spray, but currently it is difficult due to the lack of deposit geometry information. Existing methodologies are not able to measure the 3D deposit geometry inside the injector nozzle and thus a new technique which fulfils this purpose will be very helpful.
3. More optical studies should be carried out to provide a better understanding of the spray and air/fuel mixture preparation for fouled injectors (including all injector types). The data produced by using methods such as high-speed imaging, PDPA, and laser induced exciplex fluorescence techniques is also useful in validating CFD spray models.
4. Several different test cycles are needed, depending on whether the area of interest is particulate emissions, external deposits or flow rate restriction.

5. The overall effects of T90, sulphur, olefins, and aromatics on injector deposit formation in GDI engines require further study. Studies on alcohols such as ethanol and methanol are highly relevant.
6. Pre-ignition due to the present of injector deposits needs to be included within that area of investigation. Misfire/malfunction is not clearly identified to be an issue in the paper unless older technology is considered, and even then it is not clearly proven statistically. PM emissions are yet to be proven to result from injector deposits in every application of fuel injection in gasoline engines.

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Nomenclature

BSFC	Brake Specific Fuel Consumptions
CAD	Crank Angle Degree
CCD	Combustion Chamber Deposits
CEC	Coordinating European Council
CO	Carbon Monoxide
CRC	Coordinating Research Council
DISI	Direct-Injection Spark-Ignition
EDX/EDS	Energy Dispersive X-Ray
EGR	Exhaust Gas Recirculation
EMS	Engine Management System
FTIR	Fourier Transform Infrared Spectroscopy
GCMS	Gas Chromatography–Mass Spectrometry
GDI	Gasoline Direct Injection
HC	Hydrocarbon
PDPA	Phase Doppler Particle Analyser
PEAs	Polyether Amines
PFI	Port Fuel Injection
PM	Particulate Matter
SEM	Scanning Electron Microscope
T90	90% distillation temperature
TGA	Thermo-Gravimetric Analyser

VCO	Valve Covered Orifices
VD	Valve Deposits
WWFC	Worldwide Fuel Charter
XRF	X-Ray Fluorescence Analysis

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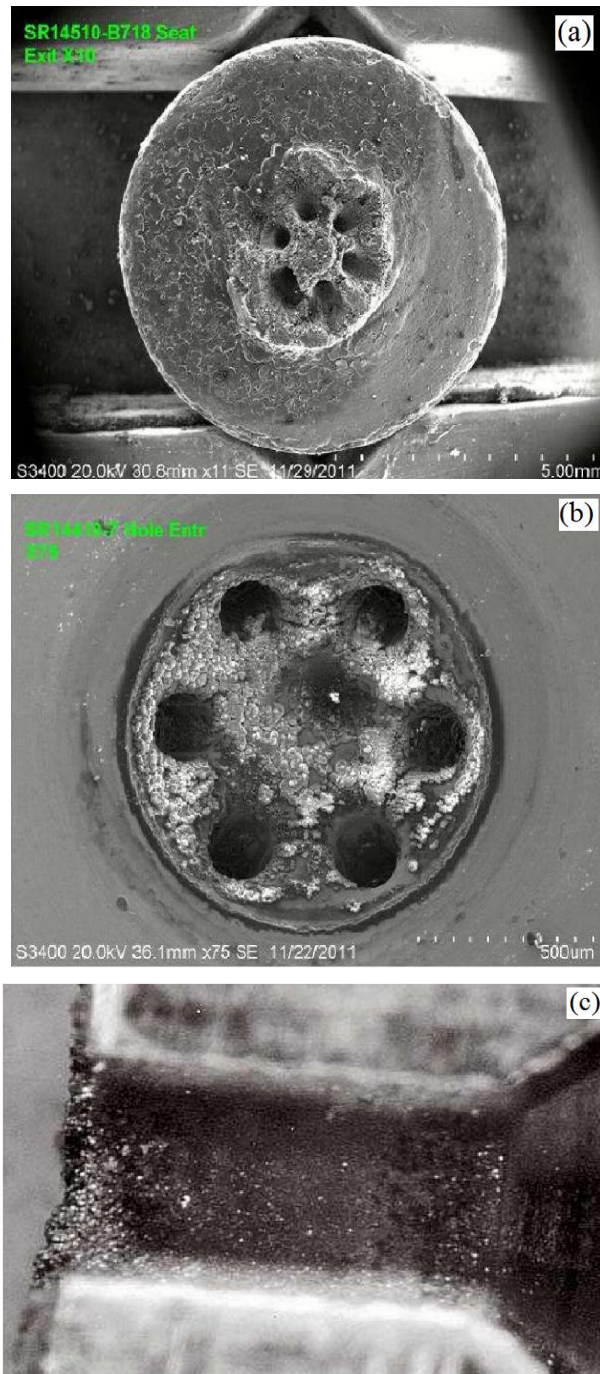


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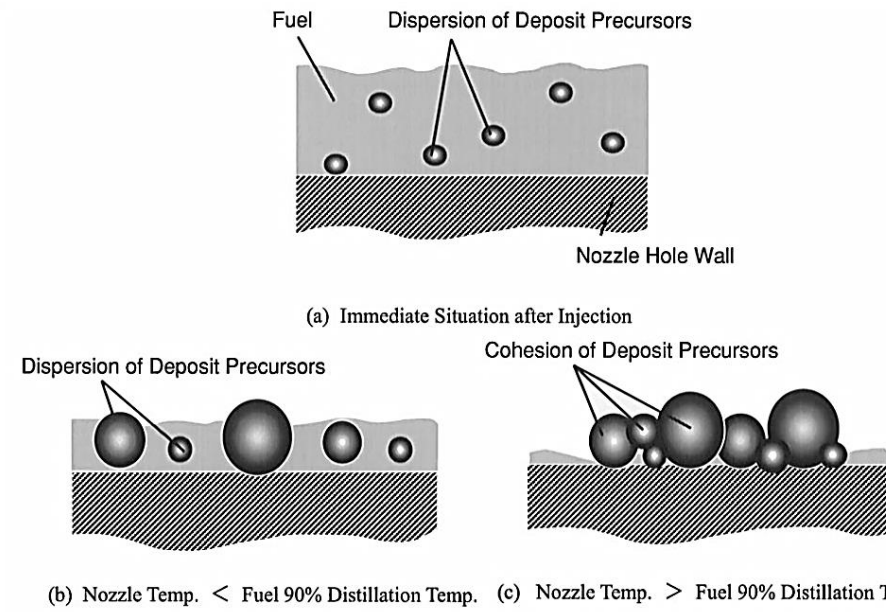


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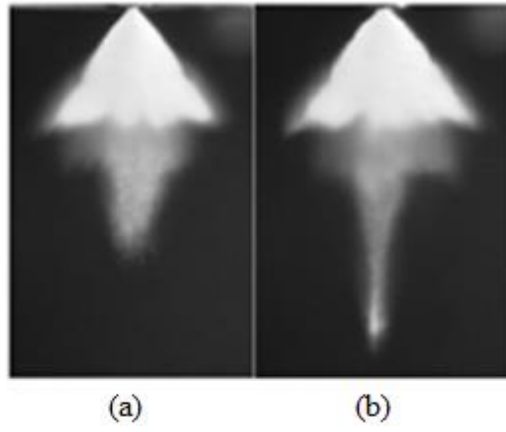
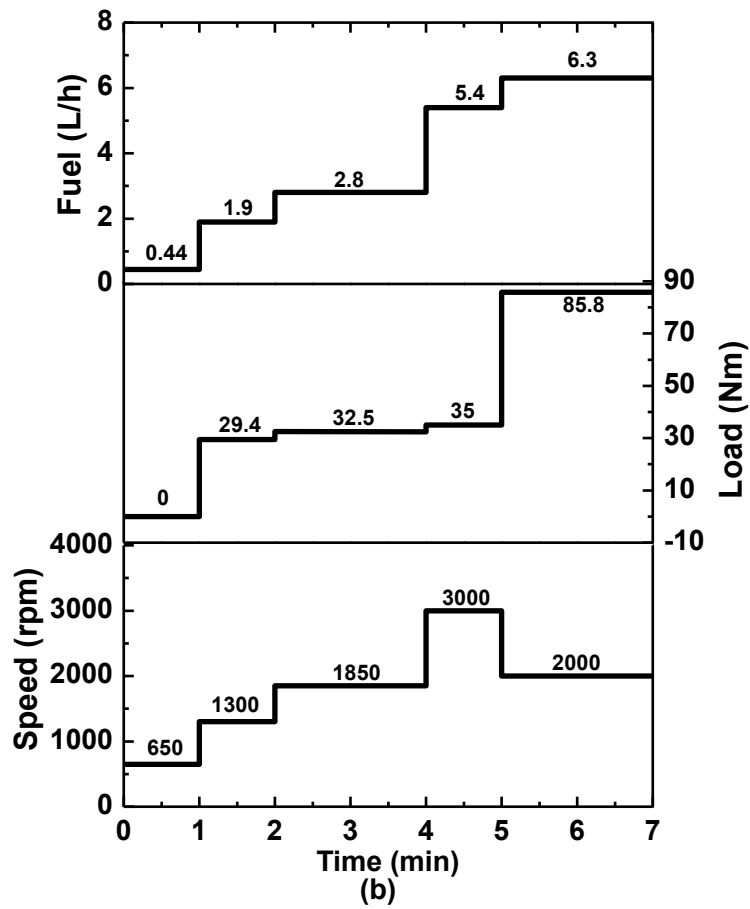
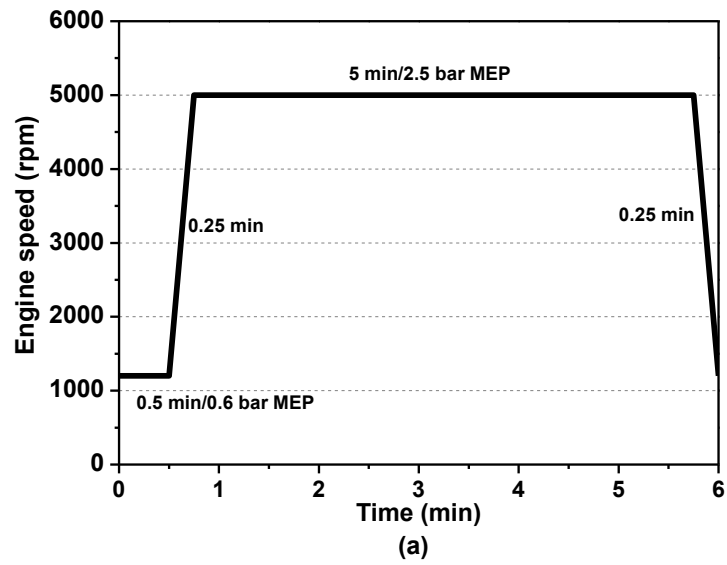


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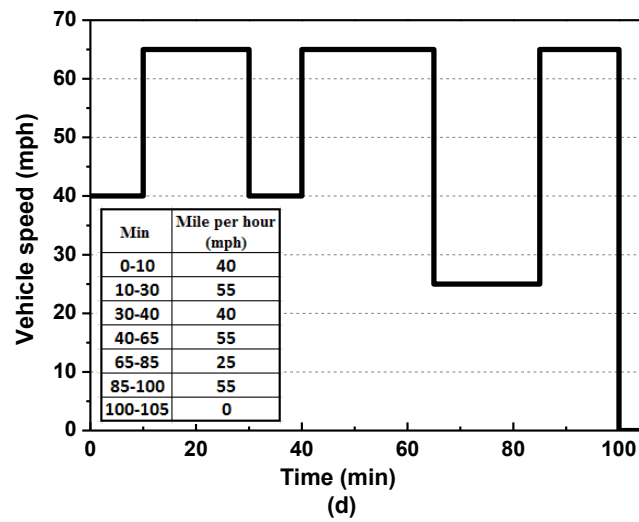
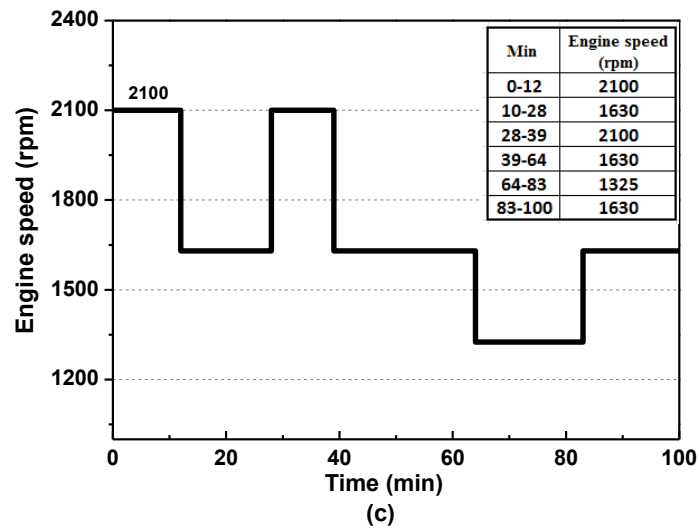


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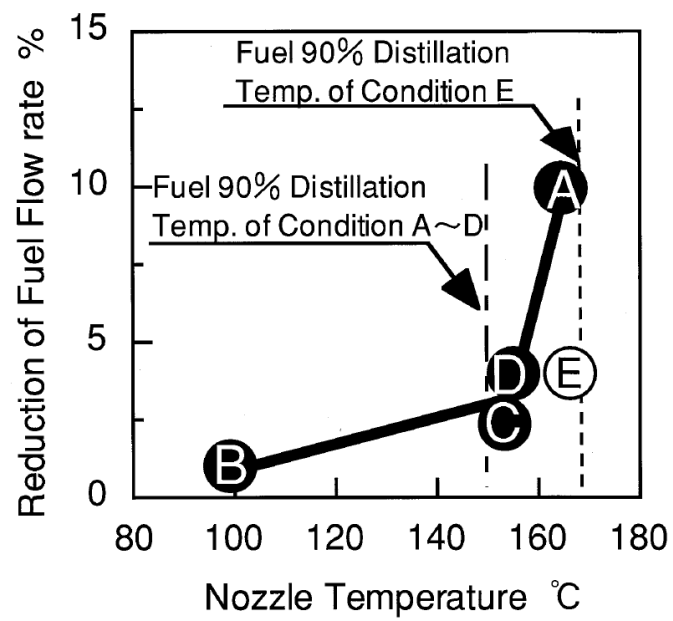


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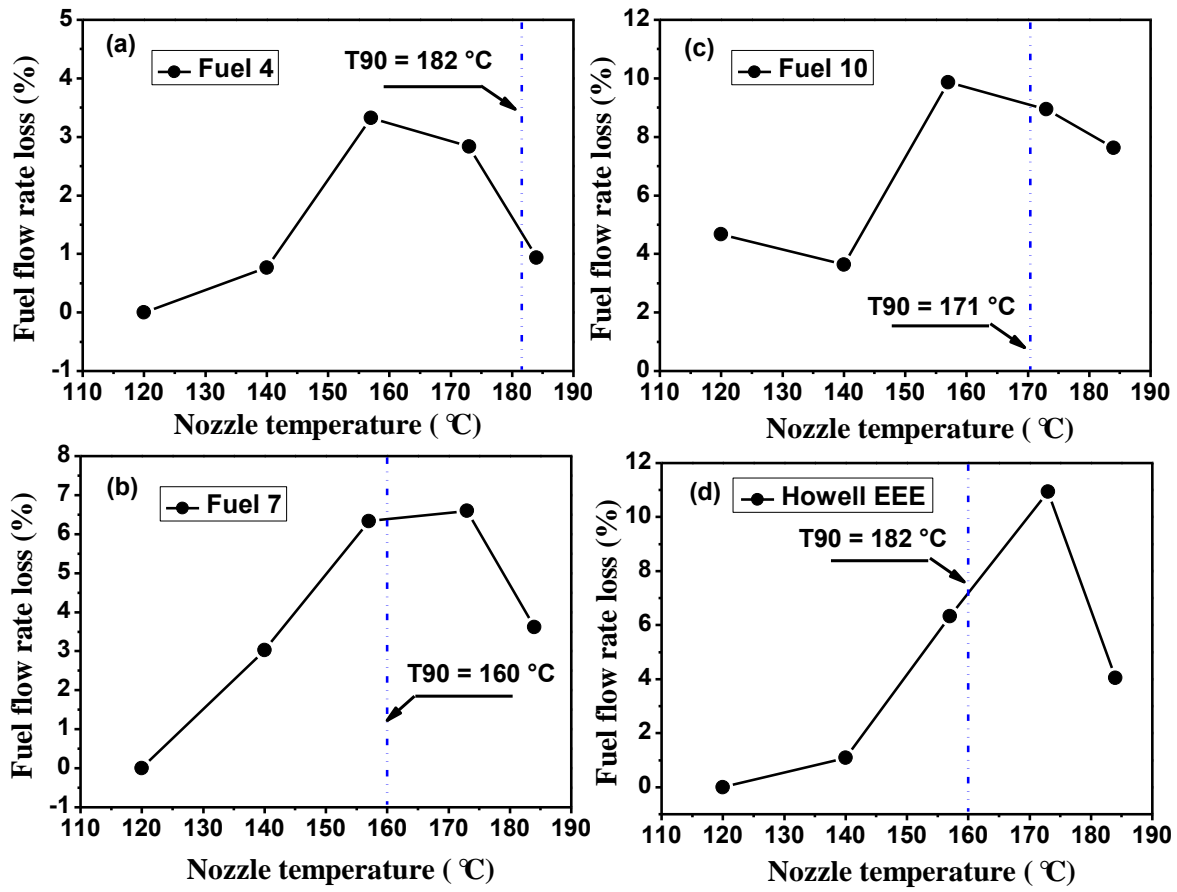
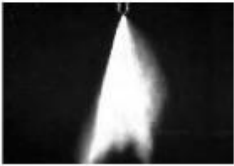
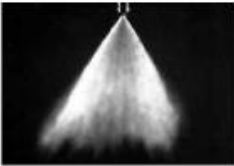
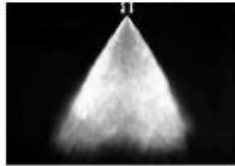
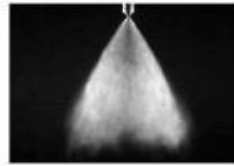






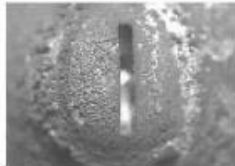



Figure 6 Reduction of injector fuel flow rate at various nozzle temperatures: (a) Fuel 4; (b) Fuel 7; (c) Fuel 10; (d) Howell EEE (the figure is drawn using the data extracted from [26], copyright by SAE International)

	Gasoline (E0)	E20	E50	E100 < ε :13 >
Spray Shape				
Nozzle				
Nozzle Hole				

※Test Conditions \Rightarrow 3200rpm, $P_{me}=0.9$, $\lambda=0.95$, Ignition Timing=MBT+4, Injection Pressure=4MPa,
 One gasket removed at nozzle tip, 10H steady state engine operation
 Injector Sample \Rightarrow NO.6 Cylinder

Figure 7 Comparison of spray shapes, nozzles, and nozzle holes after a 10 hour durability test using various ethanol blends [68] (copyright by SAE International and JSAE)

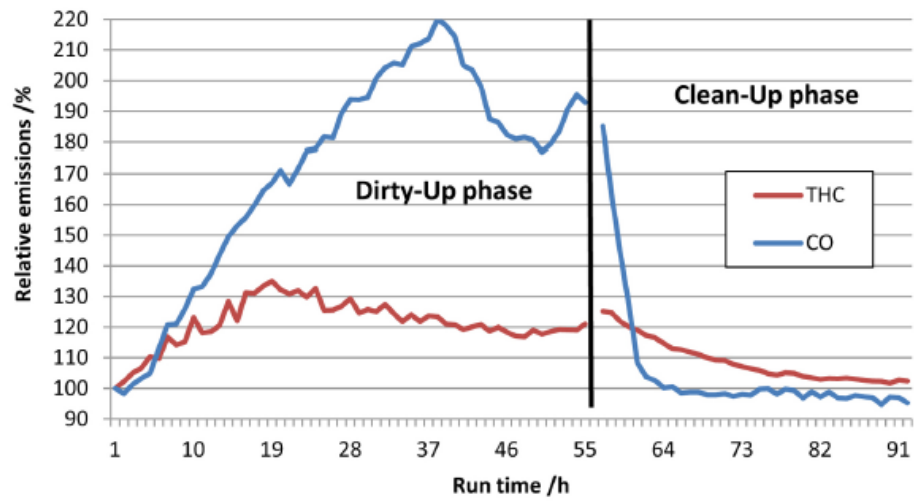


Figure 8 Relative CO and HC emissions in the dirty-up phase and clean-up Phase [79]
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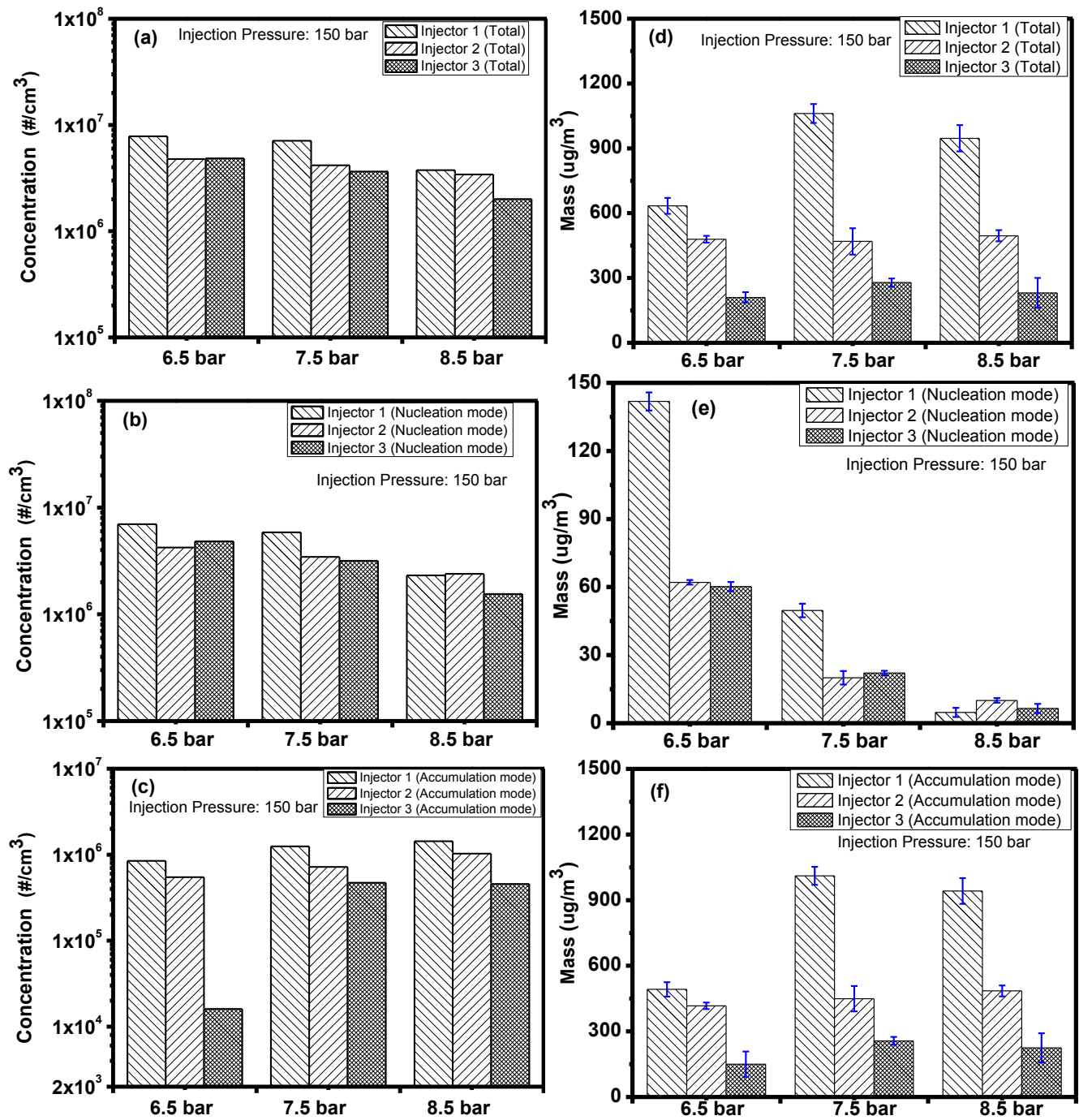


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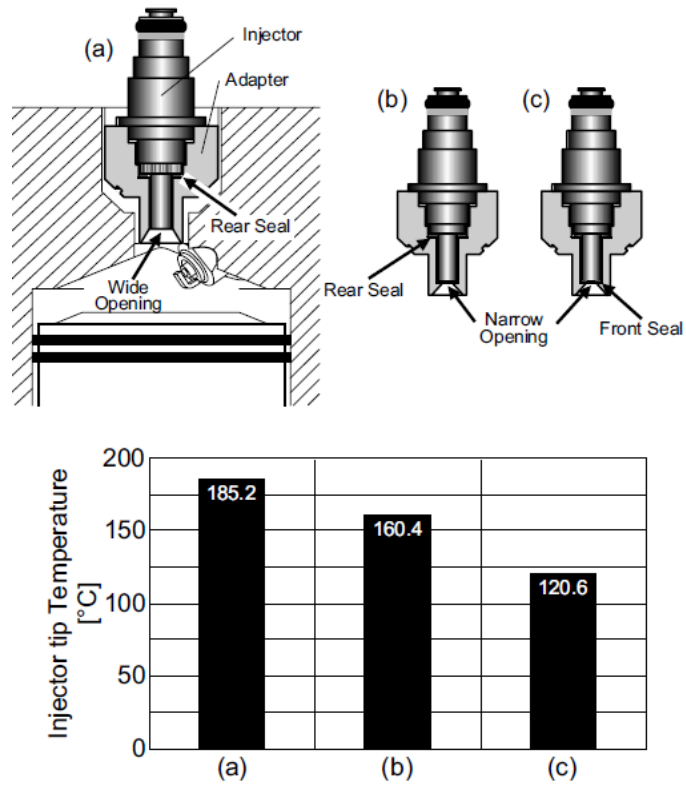


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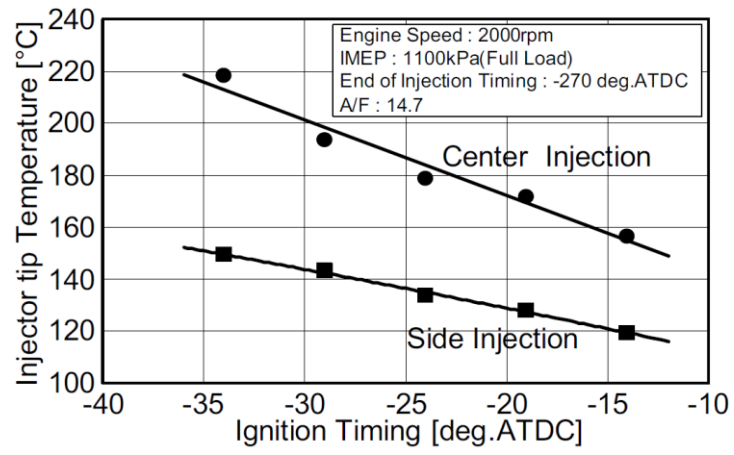


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Table 1 Summary of engine test on GDI injector deposits

Reference /Year	Cylinder number/ Compression ratio/Injection pressure (bar)	Fuel	Injector tip temp. (°C)	Coolant /Fuel temp. (°C)	Test cycle	Main conclusion
[36] /2003	4/11.5/NA	Three fuels with detergents	NA	Fuel: 22 and 45 Coolant: 78 and 93	see Figure 4 (a)	Severe and repeatable injector deposits in a 16 hour test
[79] /2012	4/10/80	Pro-foul fuel with detergent (T90: 155.3 °C Olefins: 4.3% Aromatic: 34% Sulphur: < 10 ppm)	NA	Fuel: 30 Coolant: 90	Steady state 2000 rpm and 5 bar BMEP	Deposits in side- amounted GDI injectors led to increased HC and CO emissions, and reduced fuel economy.
[18] /2003	4/NA/69	Howell EEE (base fuel) with different detergents T90: 160 °C Olefins: 1.2% Aromatic: 26.6% Sulphur: 6 ppm	173	Fuel: 32 Coolant: 85	Based on the 1995 EPA survey of driving habits in Baltimore Maryland, USA	Performance of detergents varied widely in regards to preventing GDI injector deposit formation
[47] /2001	6/NA/NA	14 fuels with different aromatic, olefin, sulphur, and oxygenated content, and different detergents	150 and 170	Coolant: 90	650 rpm Load: 30% A/F ratio: 22~33	1) T90, types of aromatics and high sulphur (>400 ppm) affected GDI injector deposit formation 2) Ethanol blend fuel and certain type of detergents led to less injector deposit formation
[22] /1999	4/12/120, 1/8/60	Seven fuels T90: 143-168 °C Aromatic: 23.2- 50.3% Gum: 0.2-18.03 mg/100 ml	NA	NA	Steady operating condition for each test point	T90 was a key factor in GDI deposit formation
[25] /2000	4/NA/69	Table 3	173 and 184	Fuel: 32 Coolant: 95	2500 rpm Loads: 500 and 600 mg air/stroke	1) Fuel detergents can be used in controlling GDI injector deposit. 2) A kinetic model was proposed
[117] /2007	4/12, 10.5 and 9.8/50, 110 and 120	Four Japanese market fuels, one US fuel, one EU fuel	NA	Fuel: 25.2 Coolant: 92	See Figure 4 (b)	A test method was developed to evaluate fuel quality with respect to GDI injector fouling
[118, 119] /2002 and 2003	4/12/50	One base fuel, One fuel with high T90, and high aromatics, One fuel with low T90 and high	NA	NA	140 km/h (10 hours) + 70 km/h (20 hours) + 40 km/h (20 hours)	1) Injector deposit formation varied with engine types. 2) High-speed operation following middle and low speed

		aromatics				conditions reduced the injector flow rate
[43] /2001	4/10.4/80	Five fuels T90: 157-182 °C Aromatic: 15-36.9% Olefins: 1.2-20.9% Sulphur: 9-49 ppm	NA	Coolant: 92	Combinations of stratified and homogeneous mode	1) Injector tip temperature, and fuel composition and property (aromatic, olefin, and T90) were the main factors in air-assisted GDI injector deposit formation 2) Lubricant did not contribute to the problematic deposit growth in air-assisted GDI injectors
[23] /2000	4/12.2/51	T90: 168.6 °C Olefins: 16.2% Aromatics: 32.5% Sulphur: 668 ppm Gum: 8 mg/100 ml	NA	NA	ASTM D5598	1) ASTM D5598 method was proven effective in screening GDI injector fouling tendencies 2) Injector fouling caused problems in engine performance and emissions
[61] /2013	4/NA/NA	Unleaded gasoline blended with cellulosic ethanol (E15 and E70)	NA	NA	See Figure 4 (c)	Bio-ethanol produced from various feedstocks had limited differences in DI injector fouling.
[37] /2009	4/NA/NA, 6/NA/NA	T90: 172.8 °C Olefin: 14.9% Aromatic: 32% Sulphur: 325 ppm Gum: 3.6 mg/100 ml Different detergents were used.	NA	NA	Figure 4 (d) 2000 mile vehicle test	1) A test cycle was developed for producing significant amounts of GDI deposit in a 48 hour test. 2) E10 reduced GDI injector deposition formation

Table 2 Fuel specifications in US, EU and China

Parameter	EU EN 228-2012	US ASTM D4814 Rev B - 2011	China GB 17930 – (Dec. 2013
Density (kg/m ³)	720-775 (at 15°C)		720-775 (at 20°C)
T10 (°C)		≤70	≤70
T50 (°C)		≤77-121	≤120
T90 (°C)		≤190	≤190
End of distillation point (°C)			≤205
E70 summer (volume %) ^a	20-48		
E70 Winter (volume %) ^a	22-50		
E100 (volume %)	46-71		
E150 (volume %)	≥75		
Sulfur (ppm)	≤10	≤80	≤(50
Aromatics (m/m)	≤35%	≤20.9%	≤40%
Olefins (%m/m)	≤18%	≤11.9%	≤28%
Max. washed/unwashed gum (mg/100mL)	5 (washed)	5 (washed)	5 (washed)/30 (unwashed)

^a Depends on volatility class of region, country and season

Table 3		Fuel properties [25] (copyright by SAE International)									
Fuel #	1	2	3	4	5	6	7	8	9	10	Howell EEE
T90 (°C)	160	182	160	182	160	182	160	182	171	171	160
Olefins (%)	5	5	20	20	5	5	20	20	12.5	12.5	1.2
Sulphur (ppm)	30	30	30	30	150	150	150	150	90	400	20

Table 4 Injector flow rate loss for various fuels at five nozzle temperatures [26] (copyright by SAE International)

	Flow rate loss at five injector nozzle temperatures (%)				
	120 °C	140 °C	157 °C	173 °C	184 °C
Fuel 1	0.00	0.63	4.79	7.03	5.18
Fuel 2	0.00	0.00	2.93	3.81	3.91
Fuel 3	0.00	0.41	4.20	8.69	7.62
Fuel 4	0.00	0.76	3.32	2.83	0.94
Fuel 5	0.00	1.13	3.84	4.52	2.73
Fuel 6	0.00	0.00	0.00	2.25	0.00
Fuel 7	0.00	3.03	6.33	6.59	3.61
Fuel 8	0.75	2.28	3.27	3.22	1.63
Fuel 9	0.00	1.68	2.52	5.49	3.81
Fuel 10	4.68	3.63	9.86	8.95	7.62
Howell EEE	0.00	1.09	6.33	10.94	4.04

Data are extracted from [26]

Table 5 Fuel properties and fuel flow rate losses [47] (copyright by SAE International)

Fuel	Base fuel	Compounds	Blend (%v/v)	T90 (°C)	Sulphur (ppm)	Flow rate loss (%)
2	Alkylate		100%	113.5	10	4
3	Alkylate	n-Propylbenzene	70/30	154.5	10	1.9
4	Alkylate	Toluene	70/30	109.5	10	6.4
5	Alkylate	p-Xylene	70/30	129.5	10	9
6	Alkylate	o-Xylene	70/30	139.5	10	8
7	Alkylate	1,2,4-Trimethylbenzene	70/30	164	10	8.8

Table 6 Summary for Injector design for controlling of injector deposit formation

Factors	Optimised design
SAC volume ^a	Orifice holes outside the Sac volume [100], or valve covered orifice (VOC) [102-104]
Tip design	Protruded injector tip is better than flat tip [100]
Combustion seal design	Not statistically significant [100] ^b
Orifice hole divergence	No taper [100]
Orifice hole surface finish	(1) Smooth finish, mechanical micro- machining is recommended [100]; (2) Laser drilling is better than EDM [101]
Hydro erosive grinding of orifice holes	No hydro erosive grinding [100]
Inlet shape	Sharp inlet [101]
Outlet shape	Step holes or counter bore [100]
Injector type	outward opening injector> inward opening swirl injector> multi-hole injector [105]

^a Defined as the volume between the valve seat and the entrance to the final metering orifice of the injector

^b Contradicts with [96]